



# Design Aspects of a High Speed Permanent Magnet Synchronous Motor/Generator for Flywheel Applications

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## Abstract

This paper presents aspects of the design solution for a high speed, high efficiency permanent magnet machine used as a Motor/Generator (M/G) unit in a flywheel energy storage system. The motor will be operated in vacuum with passive cooling; thus the right choice of permanent magnet properties and ability to withstand demagnetization due to the temperature variation and armature reaction is important for the M/G design. Additionally, the M/G will be operated with magnetic bearings so radiation is the only heat transfer method for rotor losses. Because of that, special measures are directed toward reducing the rotor losses. Analytical design results obtained by using a commercial motor design software package are presented. An investigation of the armature reaction and magnet demagnetization is performed using the magnetic circuit method and 2D Finite Element Analysis (FEA). The results of the transient 2D FEA are presented. The value of the axial force applied to the rotor due to the stator slots skew as a function of stator current is determined using 3D FEA simulation. The final design results in good torque performance over the entire operating range.

## I. Introduction

NASA Glenn Research Center is currently developing flywheel energy storage technology for use in spacecraft applications. Flywheels as energy storage devices offer some

important advantages compared to conventional batteries including high energy and power densities, long life, deeper depth of discharge, and broad operating temperature range. In addition, flywheels can be used as momentum wheels for the satellite attitude control. This presents an opportunity to combine the two satellite subsystems of energy storage and attitude control into one which leads to the advantage of reducing the overall system mass.

The M/G is a key component of the flywheel system because the energy conversion from the electrical form to the mechanical during the charge (motor) mode and from the mechanical form to the electrical during the discharge (generator) mode happens inside the M/G. The effectiveness of the energy conversion process mainly depends on the efficiency of the M/G and one of the ways to improve efficiency of the flywheel energy storage system is to design a high efficiency M/G unit.

## II. Selection of Rated Point

The M/G design procedure is shown in figure 1. The starting point for the M/G design is determination of the output power.

During its orbit cycle, the flywheel is required to maintain constant power in either charge or discharge mode and to simultaneously apply mechanical torque to the spacecraft for attitude control. Figure 2 illustrates the separated energy output power and attitude control torque loads of the flywheel during the duty cycle.

The duration of the cycle is 90 minutes. From  $t = 0$  to  $t = 60$  minutes it is charge (motor) mode, during which the flywheel is accelerating from 25 to 50 krpm. From  $t = 60$  to  $t = 90$  minutes it is discharge (generator) mode, during which

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the flywheel is decelerating in speed from 50 to 25 krpm and supplies energy to loads. At each point the net torque of M/G is equal to

$$T_{net} = T_{es} + T_{ac} \quad (1)$$

Where  $T_{es}$  is the torque component, required for the energy storage, and  $T_{ac}$  is the component required for the attitude control. The two steps shown in  $T_{ac}$  graph represent the needs in attitude control torque in motor and generator modes respectively. The  $T_{es}$  curve illustrates the torque required for a constant charge rate of 1.3 kW and a constant discharge rate of 2.6kW during the operational cycle. The output power graph represents the net torque multiplied by the maximum speed value. The point of maximum output power is located at the end of the generator mode and  $P_{out\ max} = 7.6\ kW$ .

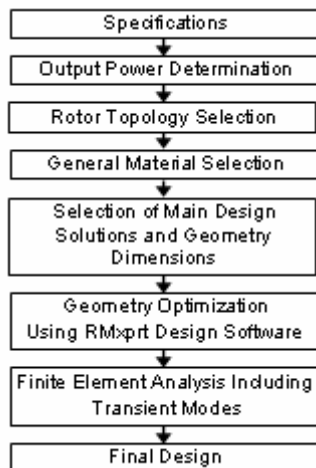


Figure 1.—M/G design procedure.

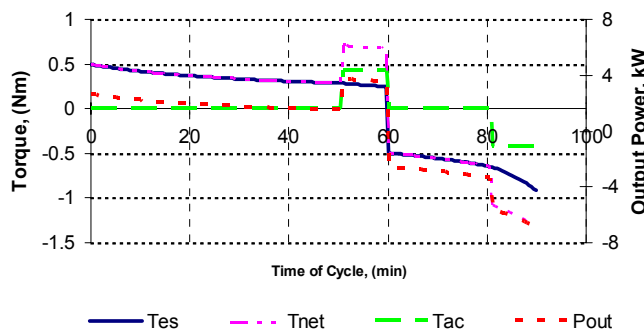


Figure 2.—Flywheel combined energy storage and attitude control output power determination.

### III. Major Objectives for the Electrical Machine Used as a Flywheel M/G

The major requirements for flywheel M/G for use in space applications are the following:

- 1) Relatively high electrical frequency of voltages and currents;
- 2) High value of power to mass ratio specific power;
- 3) High efficiency;
- 4) Low total harmonic distortion (THD) of the back emf waveform;
- 5) Low cogging torque;
- 6) Low rotor losses;
- 7) High thermal endurance, (ability to operate in vacuum without intensive cooling).

To meet the design requirements of high specific power and high efficiency, the permanent magnet synchronous machine (PMSM) was chosen. The PMSM has the advantages of high efficiency, relatively light weight, simple mechanical construction, absence of moving contacts and being maintenance free. The disadvantages of the PMSM for use in flywheel space applications include the reduced mechanical strength of the permanent magnet materials at high rotational speeds and the influence of operating temperature on the basic parameters of permanent magnets such as remnant flux density and coercive force.

### IV. Selection of Rotor Topology

The next step of the design process is the selection of the rotor topology. A study was performed to determine what type of rotor configuration best fits the requirements listed above. Three types of rotor magnet topologies were examined: surface mounted magnets (Rotor 1, 2 and 3 in fig. 3), the spoke topology (Rotor 4) and the rotor with the buried magnets (Rotor 5). The study was performed by determining the characteristics of motors consisting of the rotor topologies described above and a stator that was the same for all of the variants. The rotor outer diameter, length, type of the magnet material and the magnet thickness were kept the same for all types. All surface mounted rotors had the same pole arc angle. ANSOFT RMxpert software was used to determine the motors' characteristics. The optimization functions were the output power in the generator mode and the total harmonic distortion (THD) of the back emf waveform. Figures 3 and 4 show the results of the calculations performed.

As can be seen, the spoke and buried magnet topologies have an output power less than the surface magnet topologies. The "Rotor 1" configuration has both relatively high output power and low back emf THD value. Hence, this topology was chosen for further design

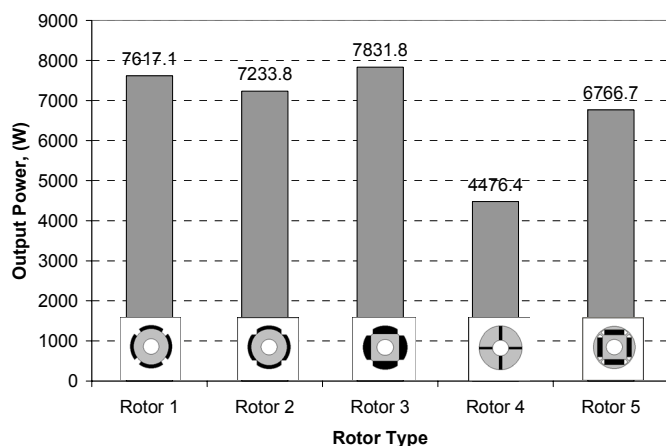


Figure 3.—Output power in generator mode for different rotor topologies.

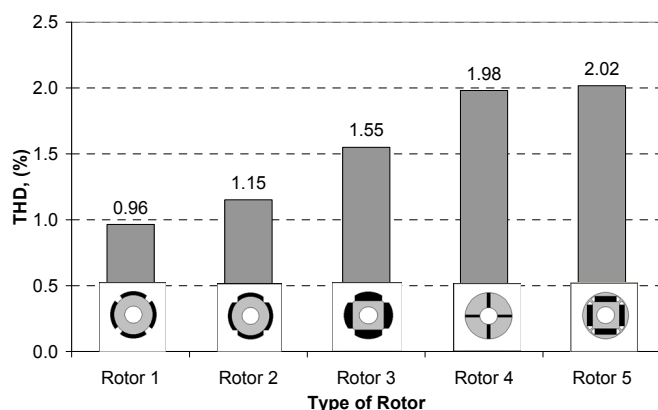


Figure 4.—Back emf THD for different rotor topologies.

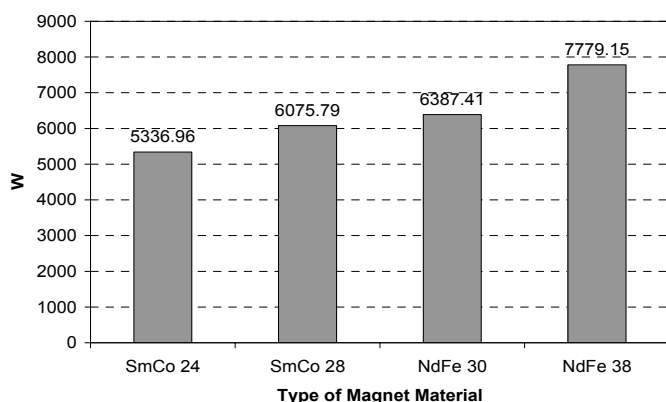


Figure 5.—M/G output power in generator mode for different PM materials.

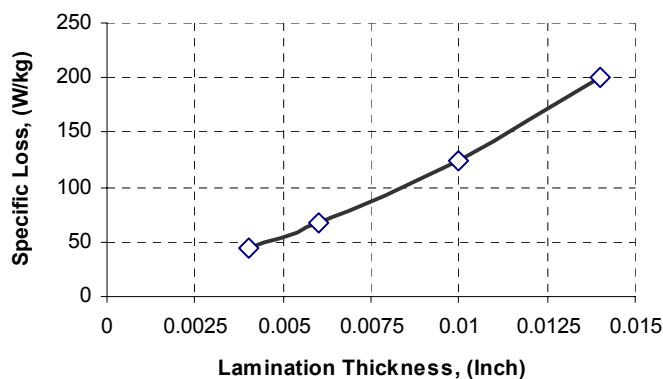


Figure 6.—Specific iron loss versus lamination thickness for a high saturation cobalt iron alloy at 1200 Hz and 2 T

## V. Main Materials Selection

The following materials have properties that greatly influence motor performance: the permanent magnet, core ferromagnetic materials, magnet wires, winding insulation. The selection of the type of permanent magnets material is an important in the M/G design because it determines the specific power of the machine and also its ability to withstand temperature variations. For the selection of the permanent magnet material, a comparison of the characteristics of motors with different permanent magnet materials was performed. The motors had the same configuration and geometrical dimensions and differed by the types of the magnet materials only. The computations were performed for the high energy product samarium cobalt (SmCo) and neodymium iron boron (NdFeB) materials. The optimization function was the output power in generator mode. Figure 5 illustrates some results of this study. As can be seen, the output power of the rotor with NdFeB magnets is higher than with the SmCo magnets. However, since SmCo magnets have a much higher temperature stability it was decided to use them for the magnet poles.

The two important characteristics of the ferromagnetic materials that have influence on the M/G performance are the maximum saturation flux density and the specific core loss. The high saturation cobalt iron alloys have high maximum saturation flux density and a relatively low specific core loss. The flywheel M/G is a high frequency electric machine. Hence, the stator core loss is a significant component of the total loss of the machine. The eddy current component of the total core loss increases with the lamination thickness. Figure 6 shows the specific core loss as a function of lamination thickness for a high saturation Cobalt Iron alloy at 1200 Hz and 2 T.

For the reduction of the eddy current component of the iron loss at high frequencies the lamination thickness should have a low value. However, very low lamination thickness can lead to fabrication problems. For this project a lamination thickness of 4 mils was selected.

## VI. Preliminary Design Output

ANSOFT RMxpert software was used to develop the preliminary designs. The input for this program includes basic electrical parameters (output power, frequency and voltage) and geometrical dimensions of the machine. The program allows specification of the magnetic and electrical properties of the materials. Also, the software can perform the optimization of the machine characteristics using the input parameters as independent variables. The output of the program gives the characteristics of the machine. Using the mentioned above software, the preliminary design and the optimization of M/G geometry was performed. The results of the preliminary design are presented in table 1.

TABLE 1.—M/G PARAMETERS

Output power, kW	7.6
Rated Voltage, V	61
Number of poles	4
Synchronous speed, rpm	50000
Outer diameter of stator, inches	5.75
Length of core, inches	0.728
Thickness of the magnet, inches	0.27
Magnet material	SmCo
Number of stator slots	24
Efficiency, %	98
THD of Induced emf, %	0.96

The M/G performance characteristics are presented in figures 7 through 9.

The RMxpert software was used for a study of the M/G characteristics during the flywheel duty cycle. These characteristics are presented in figure 10 (a) through (e).

All the voltage values were determined through an optimization process. For each frequency point the voltage value that corresponded to the maximum output power in generator mode was found. Then all the M/G characteristics were established. As can be seen, the voltage is changing with the frequency during the cycle. The current curve mostly repeats the torque profile shown on figure 2. The total losses of the M/G increase with frequency, because the percentage of the iron losses is much higher than the copper losses for this particular machine.

## VII. Armature Reaction and Demagnetization Calculation

The permanent magnet demagnetization curves are sensitive to the temperature. Also, the permanent magnets can be demagnetized by the flux component caused by the stator currents (armature reaction). The common method to check the demagnetization of the permanent magnets due to armature reaction is described in [1]. The disadvantage of

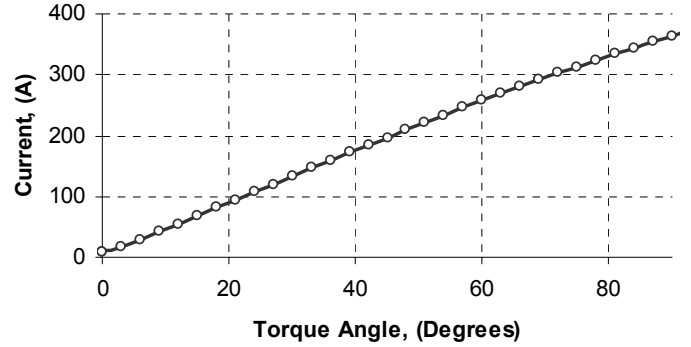


Figure 7.—M/G phase current as a function of torque angle.

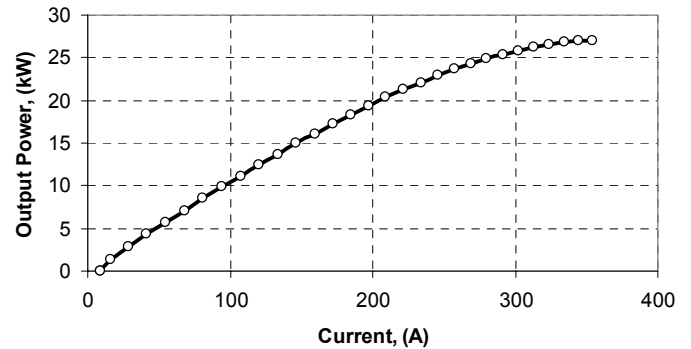


Figure 8.—M/G output power as a function of phase current.

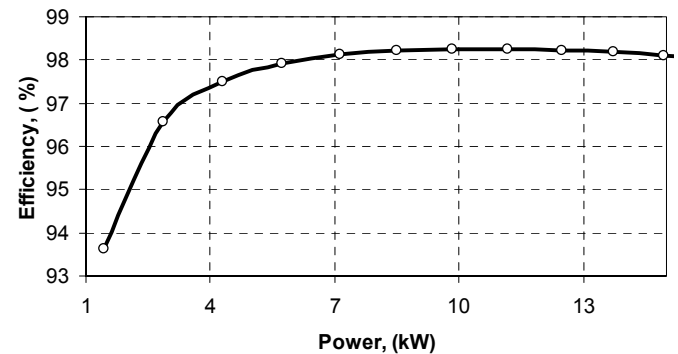


Figure 9.—M/G efficiency as a function of output power.

this method is the assumption that the permanent magnet pole has uniform saturation. A more accurate way to check the demagnetization is with the finite element method. The finite element analysis (FEA) was performed using the ANSOFT Maxwell 2D software.

First, the relative rotor-stator position and instantaneous values of the phase currents were determined. Then, the Maxwell 2D Magnetostatic model was created and the flux density distribution in the permanent magnets was determined.



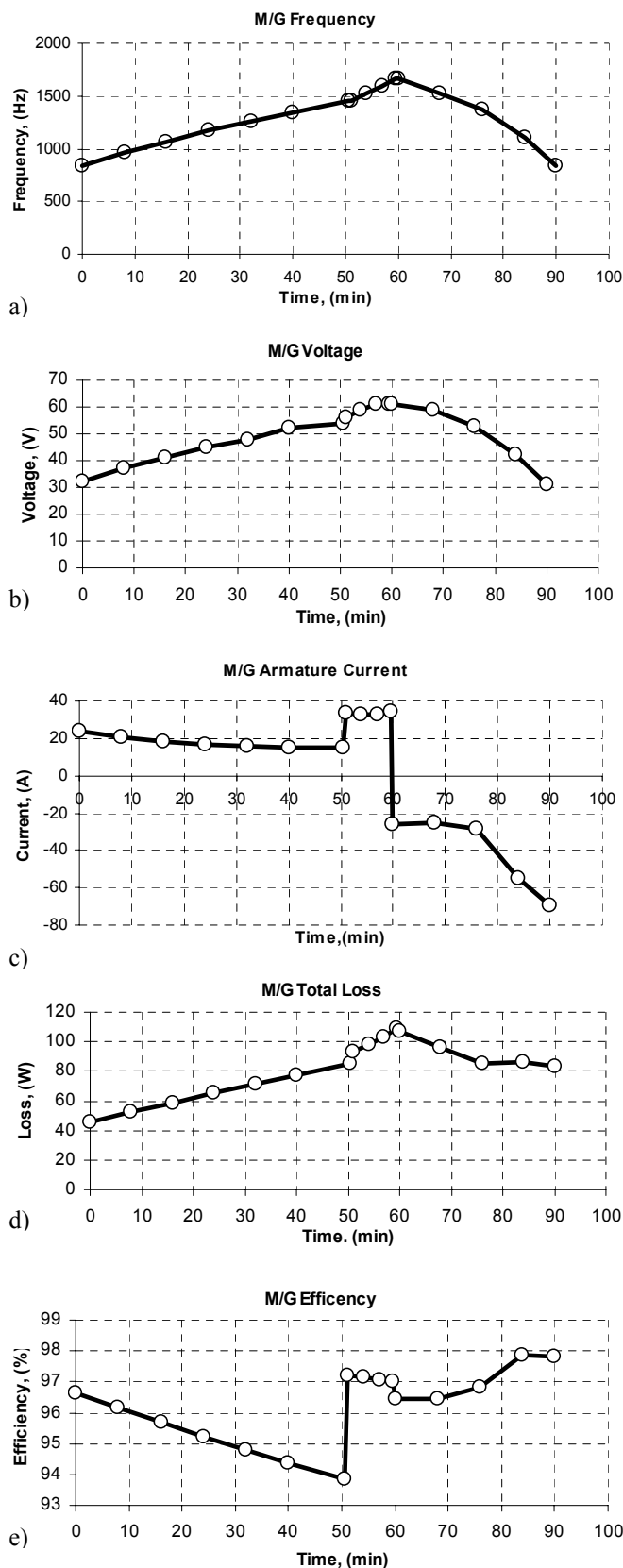


Figure 10.—M/G parameters during the duty cycle.

Figure 11 shows the flux lines in the M/G open circuit mode (no currents in the stator windings). Figure 12 shows the magnetic flux distribution in the corner area of the magnets (inside the circle) along the line starting at the magnet corner point. As can be seen, the corner of the magnet is less saturated than the other area. Figure 13 shows the magnetic flux distribution when a significant demagnetizing current reaction is presented (note the displacement of the flux lines and the decrease of the density of the flux lines). In this case, the value of the flux density in the corner of the magnet becomes small compared to the values in the areas remote from the corner. This is shown in figure 14. It was found that the corner area can be demagnetized more easily than the other areas of the magnet. Figure 15 shows the average flux density in the magnet and the flux density in the corner area as functions of peak value of the stator current. It may be noted that the corner area is demagnetized ( $B$  is negative), while the average value of  $B$  is still more than 0.5 T.

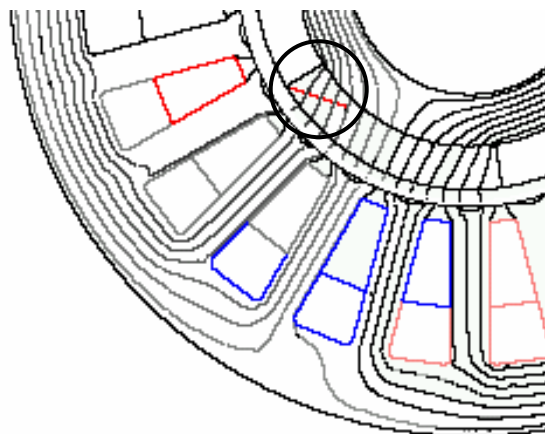


Figure 11.—M/G flux without armature reaction (permanent magnets only).

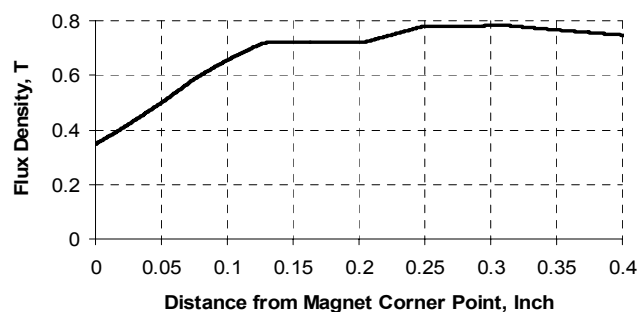


Figure 12.—Distribution of the flux density in the corner area of the permanent magnet without armature reaction.

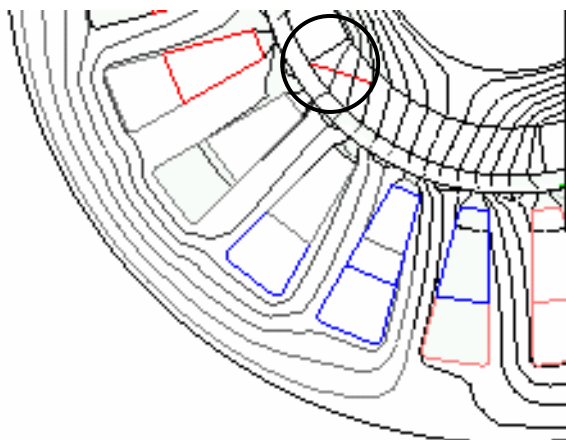


Figure 13.—M/G flux in presence of armature reaction  $I_{rms} = 297$  A.

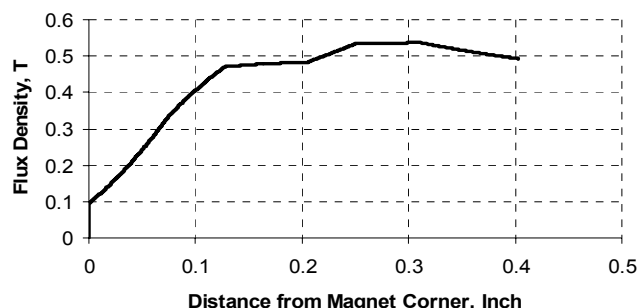


Figure 14.—Distribution of flux density in the area of the corner of the permanent magnet in presence of current reaction  $I_{rms} = 297$  A.

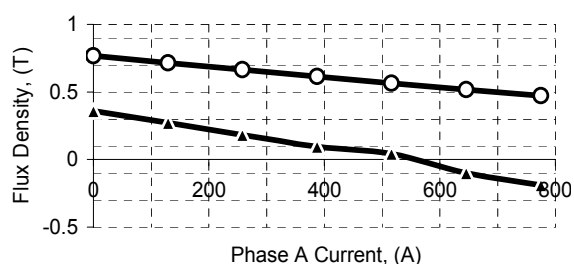


Figure 15.—Flux density in the permanent magnet as a function of a stator current.



Figure 16.—Radial and parallel orientation of the field in permanent magnet pole.

## VIII. Influence of the Magnet Configuration and the Magnetization Technique on M/G Torque Performance

It is well known that the SmCo magnets are very brittle. Therefore, the bending stress applied to the magnet pole during high speed operation could exceed the safe limit for the material. One of the ways to increase the ability of the magnet pole to withstand the high speed operation is to reduce the length of the pole arc by splitting the magnet into smaller segments (fig. 16). In this case, there are two ways of manufacturing the motor segments. The first one is to make the segments from the previously magnetized blocks, and the second is to cut segments before magnetization and then magnetize them after assembling. Each method has pros and cons. The first method is less expensive because it does not require the special magnetization fixture. For the second method, the assembling process is less laborious because the non-magnetized segments are easier to assemble. There is also a difference in the magnetic properties of the magnet poles manufactured by these ways. The magnetic field of the pole made from the segments which are machined from the magnetized blocks will have radial orientation (fig. 16 a). For the second case, it is possible to create the parallel magnetic field orientation by the proper configuration of the magnetizing fixture. The effect of the magnetic pole configuration on the motor cogging torque was investigated by the FEA. Both the current vector angle and the rotor position angle were changed simultaneously in small steps, and the value of torque was determined for each step. Figure 17 illustrates the results of this study. The maximum torque ripple for the pole with the radial field orientation is 5.15 percent and for the pole with the parallel field orientation is 2.13 percent. Thus, parallel field orientation brushless AC motors have a smaller value of the cogging torque compared ones with radial field orientation.

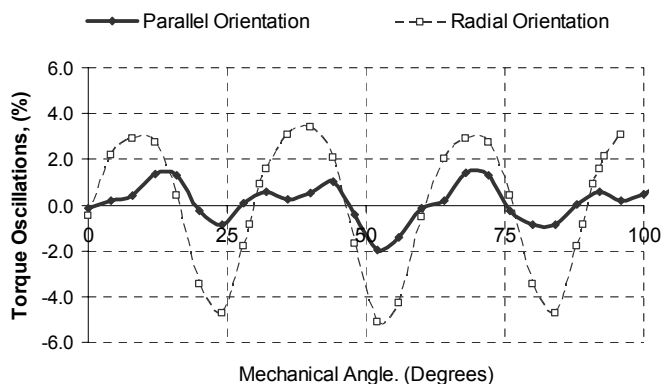


Figure 17.—Cogging torque for radial and parallel orientation.

## IX. Study of the Axial Force Caused by Stator Slot Skewing

During operation, the flywheel rotor is levitated in a vacuum and does not have any method for heat transfer other than radiation. Excessive heat can cause the damage of the flywheel rotor. Thus, rotor losses are an important factor for M/G.

One of the design solutions to reduce high frequency harmonics and induced eddy current rotor losses is to skew the stator core. However, stator skewing causes a force in axial direction that can affect the operation of the magnetic bearings. The ANSOFT Maxwell 3D software was employed to determine the value of this force. The relative rotor-stator position and instantaneous values of the phase currents were determined. Then the 3D magnetostatic model with stator skewing, shown in figure 18, was created.

Figure 19 presents an axial direction force in the M/G as a function of a stator rms current. This graph shows the linear relationship between the M/G axial force and the stator current. The force value at the rated current is 7.48 N. This value is known to be within the operational capability of the magnetic bearings.

Based on the design results presented, the high speed M/G is now fully designed and the prototype is to be fabricated and tested thereafter.

## Conclusions

This paper presents design considerations of a high speed, high efficiency permanent magnet synchronous machine for use as a flywheel motor/generator. On the basis of this study, the following conclusions can be made.

The surface mounted magnet rotor topology shows a higher output power together with an acceptable back emf total harmonic distortion level.

The finite element method allows more detailed examination of the demagnetization of the permanent magnets due to the stator currents and provides more accuracy than the conventional method, described in [1].

The ability of the SmCo permanent magnets to withstand the high speed operation can be increased by segmenting the magnet pole. The parallel magnetic field orientation shows lower cogging torque level compared to the radial one.

The skewing of the stator core causes a force in axial direction. The value of this force can be determined by 3D finite element analysis.

## Reference

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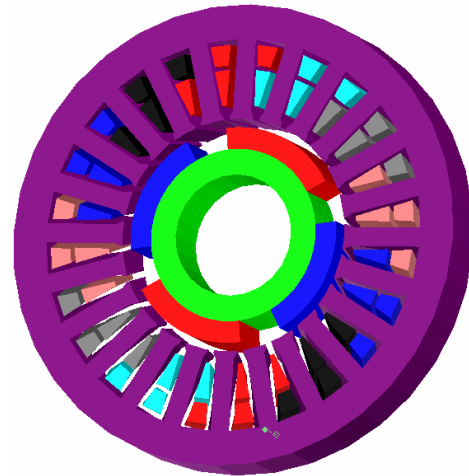


Figure 18.—M/G Maxwell 3D magnetostatic model.

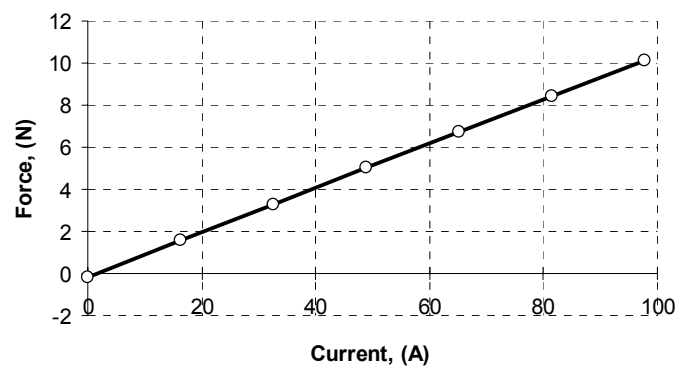


Figure 19.—Axial force caused by stator slot skewing as a function of stator current.

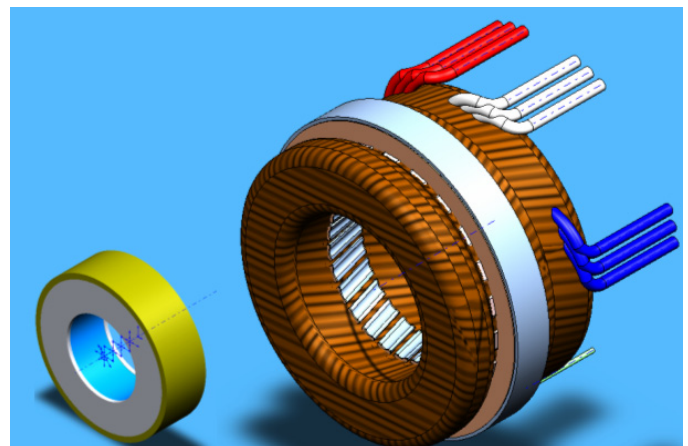


Figure 20.—Flywheel M/G solid works model.

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